Contrail coverage over the USA derived from MODIS and AVHRR data

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Abstract
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ABSTRACT:

1 INTRODUCTION

Contrails often lead to the development of additional cirrus clouds that can affect climate via the radiation budget. Evaluation of contrail coverage and optical properties is crucial for assessing the impact of current and future climatic effects of air traffic. Current estimates of contrail coverage over the United States of America (USA) have been based on a single NOAA-16 (N16) afternoon overpass time for recent studies and at four times of day for 1993-94 data from two satellites with different sensitivities and detection errors (Palikonda et al. 1999). Approximately 25,000 flights cross portions of the USA each day at different times of day. The commercial flight activity begins in earnest around 0600 LT and continues with high intensity before fading shortly before local midnight. Because spreading contrail lifetimes are generally less than 4-6 hours, the atmosphere should be cleansed of most contrail coverage by the beginning of the next day (Garber et al. 2003). Assuming that the state of the upper troposphere is, on average, the same during the day, this daily cycle should be reflected in the contrail properties and coverage. However, preliminary studies using NOAA-15 (N15)_morning overpasses suggest that the afternoon analyses may underestimate the contrail coverage because the spreading and saturation of contrails formed during the morning in areas of heavy air traffic might mask or diminish the contrails formed during the afternoon. To obtain a better assessment of the diurnal variation in contrail coverage, this study analyzes data taken during 2001 over the USA from N15 in the early morning period followed by N16 during the afternoon.

2 DATA AND METHODOLOGY

The satellite data used for this study include 1-km radiances from the morning (~0730 LT) N15 and mid-afternoon (~1430 LT) N16 Advanced Very High Resolution Radiometer (AVHRR) overpasses over the continental USA covering the domain between 25°N and 55°N and 65°W and 130°W. The domain is divided into a 30 x 65 1°-region grid. Images from all available overpasses are analyzed to calculate the contrail statistics. Only those regions having more than 90% of the expected number of pixels and having at least ten images each month are used in the monthly statistics. The Monterrey, California receiving station consistently had bad data from the N15 AVHRR resulting in the loss of many western regions in the statistics. In addition, many of the N15 overpasses for January and October yielded corrupted data and were not included in the results. The contrail mask, areal coverage, visible optical depth *OD*, and contrail longwave radiative forcing CLRF are computed as in Palikonda et al. (2002).

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3 RESULTS

Figures 1–4 show the monthly distribution of contrail cover over the domain. During April, for the morning overpass (N15, Fig 1a), maximum contrail coverage occurs over the southeastern states, off the coasts of Texas and Louisiana, and in northern Ohio. In the afternoon (N16, Fig 1b), maximum coverage occurs over North Dakota, Nevada, Washington, northern Mexico, and adjacent Pacific Ocean, areas not available from N15. The N15 maximum over the western Gulf of Mexico is still evident as a relative maximum in the N16 results. The domain averages are 1.29% and 0.71%

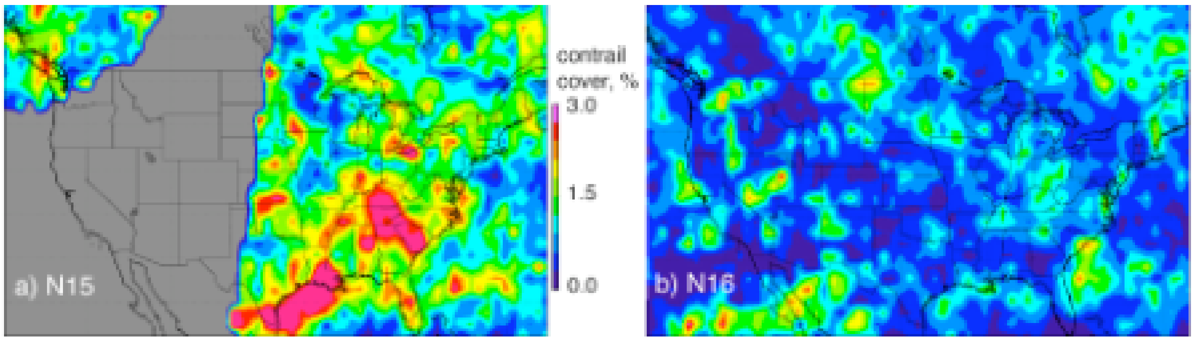

Figure 1. April 2001 daytime contrail coverage

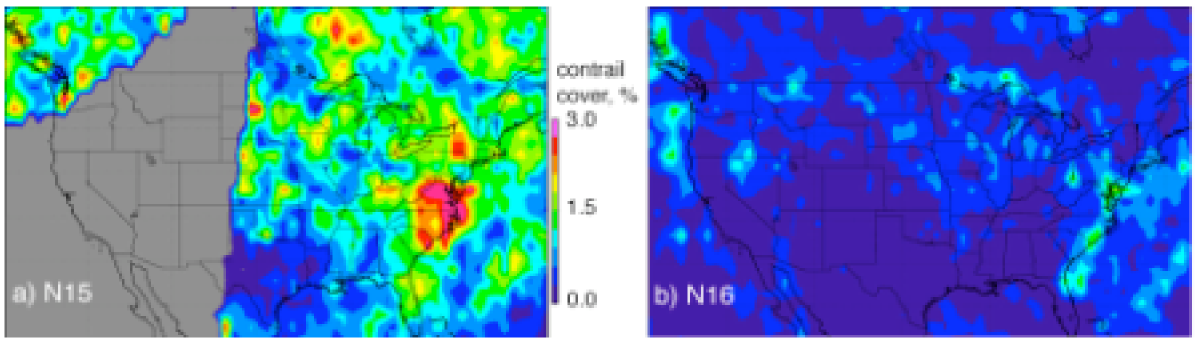

Figure 2. July 2001 daytime contrail coverage

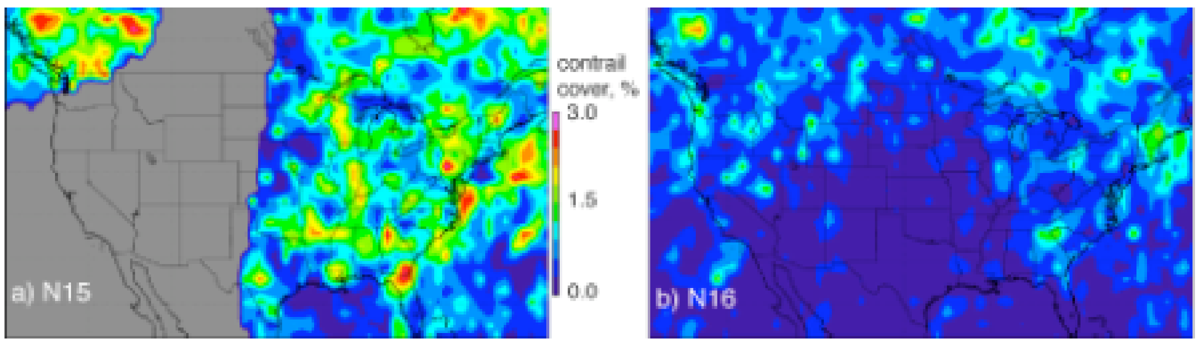

Figure 3. September 2001 daytime contrail coverage.

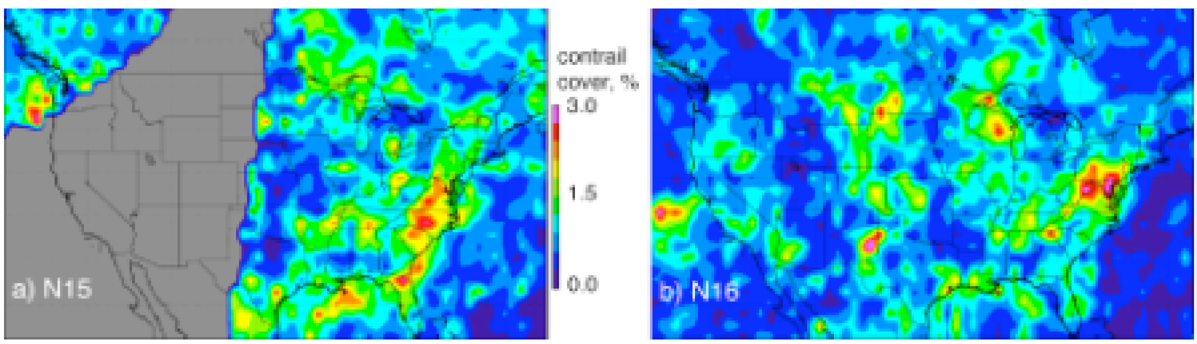

Figure 4. December 2001 daytime contrail coverage.

In the morning and afternoon, respectively. These means include differing numbers of regions. The morning July contrail cover (Fig. 2a) peaks over Virginia, North Carolina, South Carolina, and New York. Minimum coverage occurs over Texas, Louisiana, Alabama, and Minnesota. The areal coverage is almost 70% less during the afternoon (Fig. 2b). A local maximum occurred along the Atlantic coast from Maryland to Florida, and off the coasts of Oregon, Washington, and British Columbia. These areas of maximum coverage are similar to those in the N15 retrievals. The substantial morning-afternoon difference in areal coverage persists in September (Fig. 3). During the morning (Fig. 3a), maximum contrail coverage exceeds 2% over southwestern Canada, Georgia, Pennsylvania, and east of Virginia. The extensive contrail minimum in the afternoon (Fig. 3b) is defined by a triangle extending from southern California to South Dakota and to the tip of Florida. Maximum coverage occurred over British Columbia, Oregon, New England, Quebec, and Lake Winnipeg. During the winter, in the morning (Fig. 4a), contrail cover exceeds 1.5% over the southeastern states and Gulf of Mexico, off the coast of Oregon and Washington. The afternoon coverage during December (Fig. 4b) peaks over northern Virginia, West Virginia, Maryland, and Pennsylvania. Local maxima are seen over New Mexico, Wisconsin, and west of California.

The results, including the mean values for CLRF and *OD*, are summarized in Table 1 for the areas within the domain that are common to both N15 and N16 retrievals. The contrail coverage is greater during the morning than in the afternoon. Perhaps, this variation is a result of the atmosphere being cleaner (fewer flights) during early morning, so contrails are more easily observed and grow more. Also, the upper tropopheric humidity (UTH) is probably greater in the morning from previous day's convection and less in the mid-afternoon prior to convection. The coverage during the afternoon peaks during the winter and is at a minimum during July, differing by a factor of 3. The coverage in the morning is at a maximum during April and minimum during August and September. The most variation between morning and afternoon is seen during summer months, differing by a factor of 2 to 3. The least variation in coverage is during December, when the difference in UTH between morning and afternoon is probably smaller than during the warmer months. Other reasons for the difference include different sensitivities of the N15 and N16 brightness temperature differences (BTD) to the thresholds used for contrail detection and differences in the background temperatures.

The mean contrail optical depths in Table 1 vary with season to some degree. The summer maximum is around 20% greater than the February minimum. Optical depths retrieved from N16 averaged 0.29 compared to 0.26 from N15. This 12% difference is relatively consistent from month to month. The N15 and N16 monthly frequency distributions of contrail optical depth in Figure 5 are remarkably consistent. During all months, $0.2 < OD \leq 0.4$ for more than 30% of the contrails. Thicker contrails were observed more frequently in summer than during the winter and spring.

The contrail radiative forcing (Table 1) in the morning was greatest during the summer months and at a minimum during February. In the afternoon, the maximum and minimum CLRF occurred during April and July, respectively. CLRF depends on both the contrail coverage and its background. Unit CLRF, the ratio of CLRF to the fractional contrail coverage, varies from 8 Wm^{-2} in February to 18 Wm^{-2} during July in the morning. In the afternoon, CLRF varies from 6 Wm^{-2} in February to 27 Wm^{-2} during July indicating that the thermal contrast changed by a factor of 4 between winter and summer compared to a change of less than 50% between morning and afternoon.

Table 1. NOAA-15 & NOAA16 contrail properties, 2001.

Month	contrail cover (%)		*OD*		CLRF Wm^{-2}	
	N15	N16	N15	N16	N15	N16
January	N/A	0.92	N/A	0.25	N/A	0.11
February	1.19	0.93	0.23	0.24	0.10	0.06
March	1.11	0.86	0.24	0.26	0.10	0.05
April	1.29	0.71	0.25	0.28	0.11	0.14
May	1.40	0.55	0.27	0.31	0.12	0.06
June	1.17	0.44	0.26	0.30	0.15	0.04
July	1.08	0.33	0.28	0.31	0.18	0.09
August	0.97	0.38	0.27	0.30	0.18	0.03
September	0.96	0.45	0.28	0.30	0.18	0.11
October	N/A	0.71	N/A	0.31	N/A	0.09
November	1.04	0.84	0.26	0.28	0.13	0.07
December	0.91	0.80	0.26	0.28	0.14	0.07

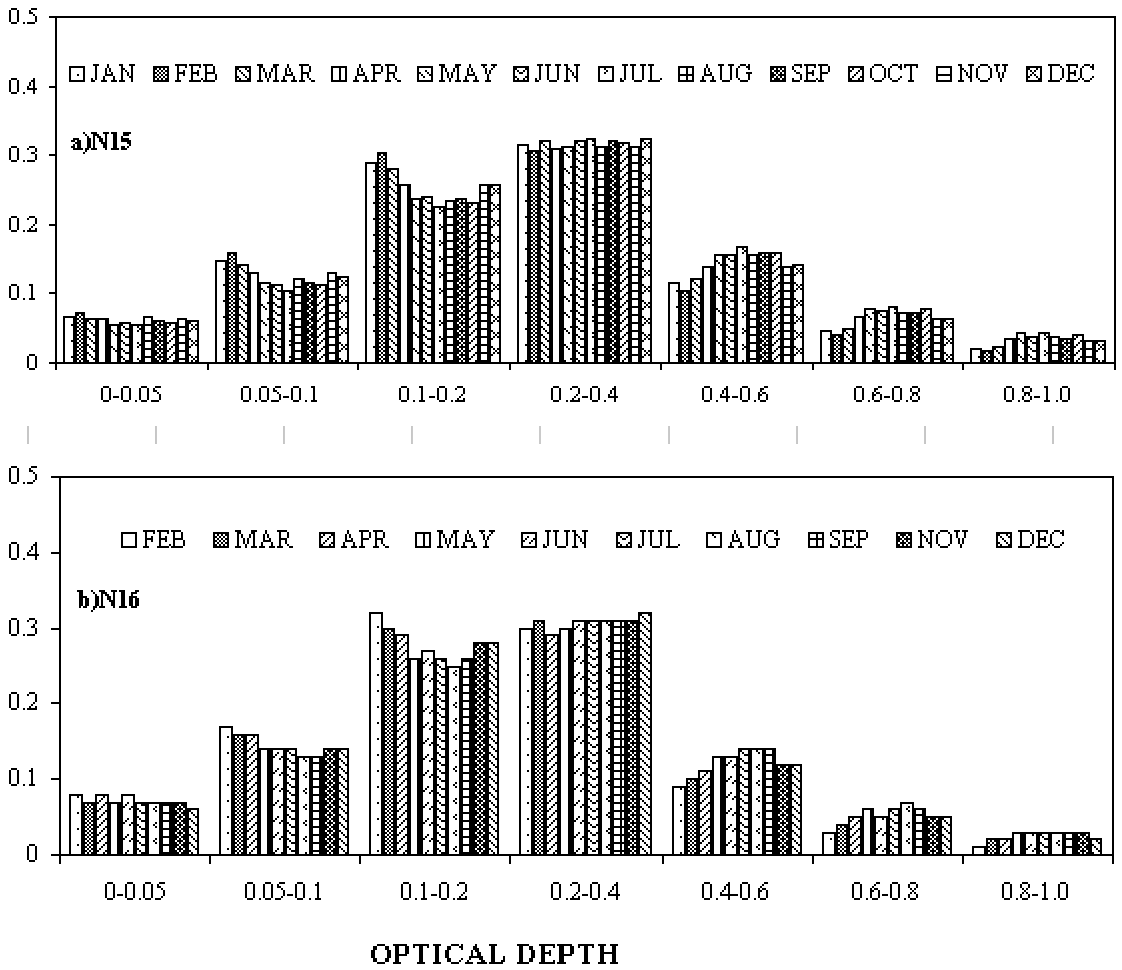

Figure 5. Histogram of daytime contrail optical depths from NOAA-15 and NOAA-16 over USA, 2001.

On average, the contrail coverage ranges from a minimum of 0.68 during August to a maximum of 1.06 in February. Between February and May, the mean varies by less than 0.08. Similarly, between July and September, it varies by only 0.03. Thus, the periods of minima and maxima are broad and the actual extrema at a given time of day or in a given year could occur in different months than February and August. The mean minimum contrail *OD* (0.235) occurred during February while the maximum average (0.295) was found during July. Mean CLRF ranged from 0.075 Wm^{-2} in March to 0.145 Wm^{-2} during September.

4 DISCUSSION

As noted earlier, the differences in contrail coverage between the two satellites may be due, in part, to different sensitivities of the 11 and 12-µm channels on the two AVHRRs. Each channel has a slightly different spectral response function and slightly different calibration. Small differences in each channel can translate to large differences in the BTD relative to the pixel-use threshold value. Visually, the BTD images from the two satellites are quite different when constructed using the same temperature range and contrast suggesting that the contrail retrievals would be different using the same methodology. The retrieval error rates have not been established yet. Palikonda et al. (1999) roughly estimated that the error rate for applying the same methodology to AVHRR data from NOAA-11 and 12 resulted in a 25% overestimate of the USA contrail coverage. Meyer et al. (2002) have developed more rigorous correction methods (e.g., false alarm rate, stationary artifacts, detection efficiency) for the NOAA-14 AVHRR contrail analysis that will be constructed for the data used here. Such techniques should account for the cirrus streaks and land forms that can be misinterpreted as contrails.

Table 2. Comparison of estimated USA contrail coverage (%).

Month	Current study 2001	Palikonda et al. (1999) 1993-94	Sausen et al. (1998) Theoretical
April	1.00	2.0	2.0
July	0.70	1.3	0.5
October	~0.85	1.9	1.9
December	0.88	2.1	1.6 (Jan)

Two conditions are necessary for contrail formation: air traffic and suitable atmospheric conditions. The air traffic over the USA is relatively heavy with more than 4000 km of potential contrails (flights above 7 km) every day in a given 1° box (Garber et al. 2003). Thus, the USA contrail coverage can be dominated by formation conditions. Duda et al. (2003) estimated the frequency of potential contrail conditions over the USA using Rapid Update Cycle (RUC) model data. Their Figure 1 showing potential coverage results for September 2001 are very similar to the afternoon contrail coverage in Figure 3. Similar correspondence was also found for November (not shown). Overall, the RUC-based potential USA contrail frequency during 2001 peaked during April at 30% and dropped to a minimum of ~12% during the summer months, nearly reaching a secondary peak in November followed by a decrease during December. The sequence is very similar to the observed contrail variation in Table 1. The contrail coverage is considerably less than the potential because the contrails can only be detected when they are not obscured by existing clouds and air-traffic coincides with the moisture. This consistency with contrail potential and the morning-afternoon optical depth consistencies in Figure 5 lend support to the relative validity of the retrievals.

Table 2 reveals that the contrail coverage is only half of that detected by Palikonda et al. (1999) from 1993-94 NOAA-11 and 12 AVHRR data and calculated by Sausen et al. (1998) using 1992 air traffic densities and multiple years of meteorological data. The relative seasonal variations between 1993-94 and 2001 are nearly identical. Because the air traffic should have increased by more than 30% or more between 1992 and 2001 (e.g., Minnis et al. 2003a), the contrail coverage should have increased. Part of the reduction may be due to missed contrails in the N16 images and to overestimates in the N11 and N12 analyses. Additionally, it should be repeated that the averages in Table 1 and for 2001 in Table 2 do not include a large portion of the western USA (Fig. 1), an area that is likely to account for less contrail coverage than the eastern USA. Minnis et al. (2003a) found a decrease in the frequency of persistent contrails over the USA during 1999 relative to 1993-94 that corresponded to a drop in upper tropospheric humidity (UTH) as indicated by the mean relative humidity (RH) at 300 hPa from the National Center for Environmental Prediction (NCEP) reanalyses data. As seen in Figure 6, the UTH was 45.5% during 1993-94 and dropped to 39.4% during 2001, one of the lowest values during the 30-year period. Since RH is a crucial factor in the formation of contrails, a reduction in RH should result in reduction of contrail cover. From correlations of mean cirrus cloudiness and UTH in areas without heavy air traffic, Minnis et al. 2003b found that cirrus coverage decreases by an average of 0.4%/% UTH. Thus, the cirrus amount would have diminished by ~2.5% over the USA between 1993-94 and 2001 and would likely include a decrease in contrails.

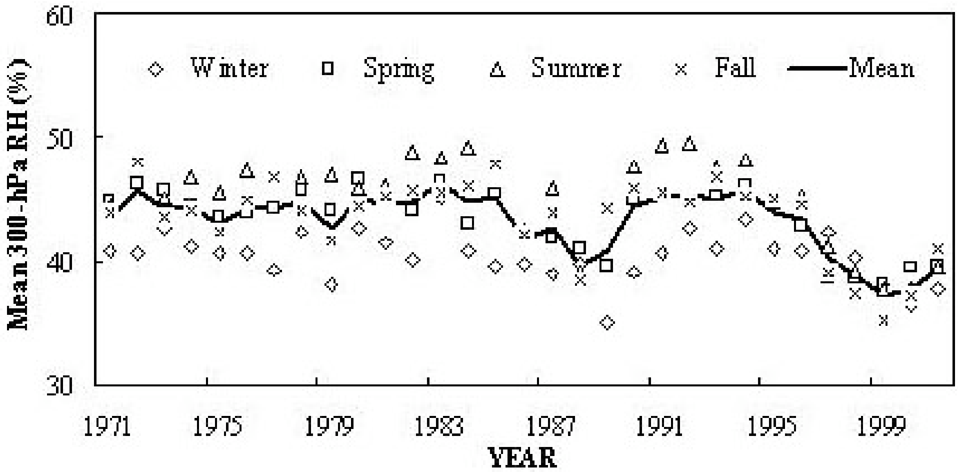

Figure 6. Seasonal and annual mean NCEP RH at 300 hPa over USA.

The phasing of the observed seasonal cycles in contrail coverage differs from the theoretical results of Sausen et al. (1998) in Table 2 and Ponater et al. (2002), but is consistent with the contrail frequency observations from surface observations (Minnis et al. 2003a). The observed seasonal range (200%) is only half of that (400%) observed from the surface and computed theoretically. This range difference decreases if only the N16 values are used. This discrepancy and the large N15-N16 contrail coverage difference during summer suggest that the N15 coverage could be overestimated during the summer. Additional analysis is needed to confirm this indication.

The seasonal variation in *OD* is similar to that computed by Ponater et al. (2002) with a maximum during the summer. Similarly, the greater occurrence of optically thick contrails is consistent with the greater maximum contrail optical depth computed by Ponater et al. (2002). However, the theoretical winter minimum relative to the summer maximum is significantly less than the observations. On average, the observed *OD*s are twice the value of those computed theoretically. The CLRF values also are considerably larger than those derived by Ponater et al. (2002). Part of the difference is due to *OD* discrepancies. The remaining differences are likely a result of differences in the background temperatures and the diurnal cycle in contrail coverage that is not included here.

5 CONCLUSIONS

The preliminary results shown here confirm, for the most part, the relative seasonal variations in contrail coverage and optical depths. Over the USA, contrail coverage peaks during the large winter and early spring and bottoms out during the late summer. Contrail optical depth is greatest during summer. Uncertainties in the magnitudes of contrail coverage, optical depth, and radiative forcing are still large. Refinement of the automated contrail detection methods and detailed error assessments are needed to help resolve some of the remaining large differences between the theoretical calculations and the observations. Until these improvements are implemented, it will not be possible to determine conclusively if the current model estimates are sufficiently accurate for estimating contrail climate effects or whether additional improvements are needed. It is clear that interannual variations in UTH can have a large impact on contrail frequency and coverage. Such variability should be manifest in multi-year modelling results.

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